Redouane MEHIMDA, Mohammed MESSAAD, Mokhtaria SIALI

University of Sciences and Technology of Oran, USTO-MB, FGE, BP 1505 El M'Naouer, 31000 Oran, Algeria

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Heating of an electrical contact by a vacuum arc

Abstract. *The electric arc is a self-sustained electric discharge characterized by a very high current density at the cathode and a low cathode voltage. This corresponds to high power densities causing heating, melting and evaporation of the electrical contact. The erosion of an electrical contact implies a limitation of the lifetime of the electrodes in the electric interruption devices. The cathode and anode spot are defined as superheated regions of cathode and anode surfaces from which the metal vapor emerge. The Heat sources of a contact are the Joule heat produced by the current and the impinging positive ions on the surfaces. The hot surface emits electrons and metal vapor.*
In this paper, the heating process of an electrical contact with an electric arc in vacuum is considered. We present a numerical simulation of an electrical contact heated by an arc in vacuum for tungsten, copper and aluminum electrodes. The purpose is the identification of the main source of heating of the electrical contact in vacuum arc discharge. We also investigate the time needed for an electrode to reach the melting and vaporization temperature and compare these times to those experimentally obtained by some authors on arcs with duration less than 100 nanoseconds.

Streszczenie. *W artykule analizowano proces nagrzewania elektrod kontaktu w próżni. Przedstawiono numeryczną symulację nagrzewania przez wyładowanie elektryczne. Analizowano też czas po którym metal topnieje I odparowuje.* ***Nagrzewanie elektrycznych kontaktów przez wyładowanie w próżni***

Keywords: vacuum arc, electrical contact, heating, melting, vaporization, cathode spot.
Słowa kluczowe: wyładowanie elektryczne, nagrzewanie, kontakt elektryczny.

Introduction

The electric arc is a self-sustained electric discharge characterized by a very high current density of up to (1×10^{12} $A.m^{-2}$) and a relatively low cathode drop *(< 25 V)* [1-25].

An electric arc develops in vacuum as well as in a gas. The conducting medium comes from the vapor coming from the electrodes and especially from the cathode. After created, the emitted metal vapor fills the entire space between the electrodes. In fact, it is no longer an arc in a vacuum, but in the metallic vapor. As this last does not exist before the arc and disappears quickly after the extinction, we maintain the notion of arc in the vacuum. All properties of the vacuum arc discharge are conditioned by the processes occurring in the cathode spots. The cathode spot is a small luminous region on the cathode surface which carries the current between the cathode and anode. The metal vapor also comes from the cathode spot.

Jüttner [11, 12] studied arc spots on a copper cathode with a high speed camera with fined for with spatial resolution ≤ 5µm and time resolution of ≤10ns. The current was of 30–70 A. He found spots with diameters of 10–20 µm. These spots appear and disappear cyclically in less than 100 ns. He concluded that that a time <100 ns is sufficient for initiation, development and death for the cathode spot in vacuum. For a copper cathode, Daalder [13] found a spot of diameter 6 µm and lifetime about 100 ns. For Ecker [14] and Rakhovsky [15] these quantities are ≥*1µs* and ≥100 *µm,* respectively.

For Mesyats [4], the spot lifetime is always some ns. Analyzing craters formed on the cathode surface Juttner [16] and also Puchkarev [8] showed that craters with a diameter of about 5 *µ*m can be formed in times less than 100 ns. Anders [9] using a laser absorption techniques found a diameter of *20 µ*m and a lifetime of *10 ns* for copper cathode spot.

Table 1 gives some values of the radius of the cathode spot obtained experimentally in vacuum arc discharge.

An electrical contact is heated on its surface and in its volume. Joule effect represents a volumetric (internal) heat source designated here by q_v and the heat flux of arc plasma acting on the surface of the contact represents a surface heat source designated here by q_s. The power density received from the arc plasma on the surface q_s is:

(1) $$q_s = q_i + q_{er} + q_r + q_n$$

where q_i *is* power density received by the positive ions from the ionization of the metal vapor in the positive column, q_{er} is power density received from the backscattered electrons of the positive column, q_r is power density received from the column radiation and q_N represents the nottingham effect [1-5, 17, 18].

Table1. Dimension of cathode spot in vacuum for a copper cathode and a current less than 50 A.

Authors	Analysed quantity	Spot radius (µm)
Daalder [5]	Crater	3
Djakov [6]	Light emitted by the spot	5
Puchkarev [7]	Crater	5 à 6
Anders [8]	Light emitted by the spot	3
Mesyats [4]	Crater	0.3
Jüttner [10,11]	Light emitted by the spot	2.5 - 5

Simulation

We will study the heating of an electrical contact (anode or cathode) by a surface heat source and by volumetric one. The aim the study is to estimate the required time for the metal contact to reach the melting temperature and the evaporation temperature. This study must give an order of magnitude of the different power densities and compare their importance.

The existence of protrusions (tips or pointes) on an electrical contact is inevitable. The creation of an arc in the vacuum begins with the emission of electrons by electric field effect mainly on the surface of these tips. That is why we take the case of a contact having on its surface a truncated conical tip of height *h=1mm*. The radius of the base is R_2*=1mm* and the radius of the upper surface is R_1*=50 µm*. This tip is heated by an electric arc of radius r_s*=10 µm.* The shape of the tip is drawn in Figure 1.

To determine the evolution of the temperature at the surface of the contact, we solve the heat equation with the initial conditions and the boundary conditions as follows:

(2) $$\rho c \frac{\partial T(r,z,t)}{\partial t} = \lambda \Delta T(r,z,t) + q_V$$

(3) $$\frac{\lambda \partial T(r,0,t)}{\partial z} = -q_S , 0 \le r \le r_S$$

(4) $$\frac{\lambda \partial T(r,z,t)}{\partial z} = 0 , r \succ r_S$$

(5) $$T(r,z,0) = 300\ K$$

(6) $$T(r,\infty,t) = T(\infty,z,t) = 300\ K$$

where, c is the specific thermal capacity, λ is the thermal conductivity and ρ is the density of the contact material. t is time, ΔT is the laplacian, q_v and q_s are the volumetric and surface heat power densities.

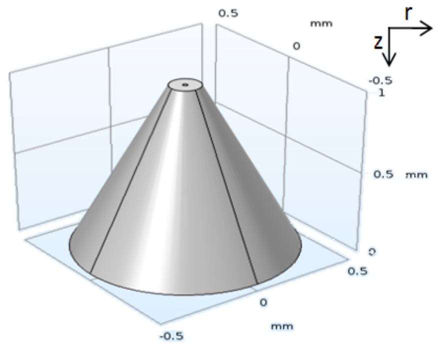

Fig.1. Shape of a tip on an electrical contact heated by an arc.

The resolution of the heat equation is done by the finite element method using the Comsol multi-physics tool. The materials physical properties of the contacts used are given in Table 2.

Table 2. Physical Properties of Materials

	λ W/ m.K	ρ Kg/m^3	c J/Kg. K	T_m K	T_v K
Tungsten	175	17800	132	3695	5828
Copper	400	8700	385	1356	2868
Aluminium	237	2700	904	933.3	2782

Results

Figure 2 shows the variation of the spot temperature as a function of time for a volumetric power density $q_v = 1{\times}10^{12}$ W/m^3 for a tungsten contact. It is seen that the evaporation temperature is reached after 15 ms. On the other hand, if the contact is heated by the same power density but on its surface then this time is reduced to 30 ns (Figures 3).

Figures 4 and 5 show the variation of the spot temperature as a function of time for a volumetric power density q_v = $1{\times}10^{12}$ W/m^3 and surface power density q_s = $1{\times}10^{12}$ W/m^2, respectively for a copper contact. The same results obtained for an aluminum contact are shown on Figures 6 and 7.

The results are also summarized in Tables (3-8) giving times for reaching the melting temperature (T_m) and the vaporization temperature (T_v). In Table 3, we give the appearance time of the liquid phase and the vapor phase as a function of q_s for tungsten. It can be seen that as the surface heat power density increases these times become shorter.

For a value of $q_s = 1{\times}10^{12} W/m^2$, the appearance time of the liquid phase is 18 ns and that of the vapor phase is 30 ns. If the contact is heated in volume then the appearance time of the liquid phase and the vapor phase are significantly higher (Table 4). Indeed, for a value of the volumetric power density $q_v = 1{\times}10^{12} W/m^3$ these times amount to 9 and 15 *ms*, respectively.

The results for the copper case are given in Tables 5 and 6. The evaporation temperature is reached in a time of 20 ns if the contact is heated by a surface power density $q_s = 1{\times}10^{12}$W/m^2. But if it is heated in volume by the same power density value $q_v = 1{\times}10^{12}$W/m^3 this time is 10 ms.

Similarly, for an aluminum contact, the vapor appears in a time of 13 ns if it is heated on the surface but in 7ms in the case of heating in volume (Tables 7 and 8).

The appearance times of the liquid phase and the vapor phase for aluminum are lower than those of copper, which in turn are lower than those of tungsten.

It should be noted that, in reality, the effective appearance time of the liquid phase and the vapor phase are longer because a certain amount of energy is spent during the change of solid-liquid phase and liquid-vapor. As seen previously for a copper contact heated by a surface power density $q_s = 1{\times}10^{12}$W/m^2 as an example, the vapor appears in a time of 10ns. Consequently, spot lifetime of *100ns* is plausible. To obtain short lifetimes, the surface power density q_s must be larger than $1{\times}10^{12}$W/m^2. Physically, after the birth of the spot on the cathode for example, the electrical contact is heated intensively at the surface with positive ions and also with joule heat. The result is an intensification of emission of electron and vapor. The radius of spots increase with time until a maximum value represented approximately by the crater radius. This is because the contact is also cooled by Nottingham effect, heat conduction, evaporation, radiation and droplets emission. At the time corresponding to the maximum spot radius, the spot can be considered as been in equilibrium i.e., the power heating is balanced by the power cooling the spot. This time is designated by the spot lifetime. Just after, the power cooling the spot becomes larger than that heating it. The emitted electron current density and vapor quantity decrease until the extinction of the spot.

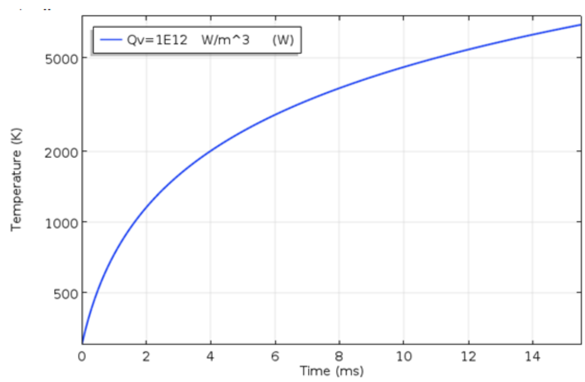

Fig.2. Variation of the surface temperature as a function of time for a volume power density q_v = $1{\times}10^{12}$ W/m^3 for a tungsten contact.

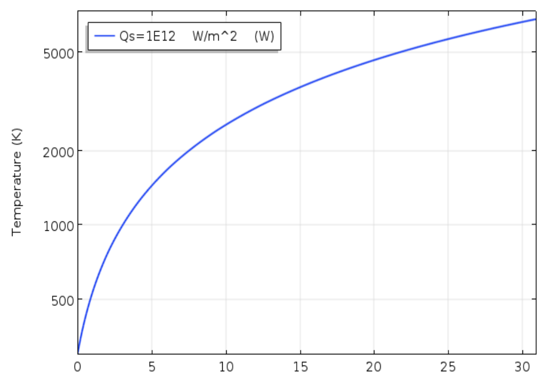

Fig.3. Variation of the surface temperature as a function of time for a surface power density q_s= $1{\times}10^{12}$ W/m^2 for a tungsten contact.

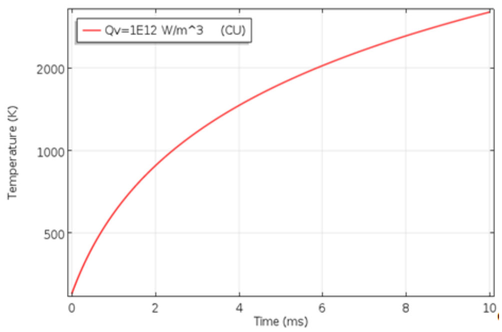

Fig.4. Variation of the surface temperature as a function of time for a volume power density $q_v = 1 \times 10^{12}$ W /m^3 for a copper contact.

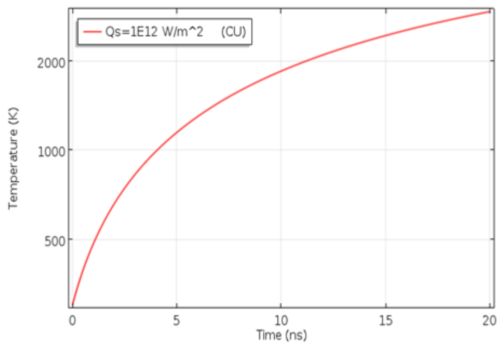

Fig 5: Variation of the surface temperature as a function of time for surface power density $q_s = 1 \times 10^{12}$ W/m^2 for a copper contact.

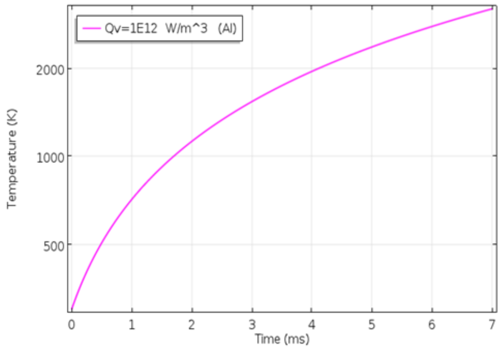

Fig.6. Variation of the surface temperature as a function of time for a volume power density $q_v=1 \times 10^{12}$ W/m^3 for an aluminum contact.

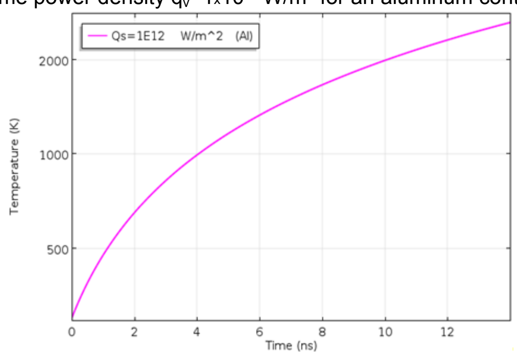

Fig.7. Variation of the surface temperature as a function of time for a surface power density $q_s= 1 \times 10^{12}$ W/m^2 for an aluminum contact.

To heat the contact surface to vaporization temperature with a volumetric source alone in some nanoseconds it is necessary to have power densities much larger than 1×10^{12}W/m^3.This must correspond to current density must larger than 1×10^{11}A/m^2 and an electric field at the cathode surface much larger than 1×10^9 V/m. These orders of magnitudes are in accordance with those already obtained by us with a stationary arc cathode spots in vacuum [1] and those of Mesyats [1].

Table 3. Appearance time of the liquid phase and the vapor phase as a function of q_s for tungsten

$q_s(10^{11}$W/m$^2)$	T_m=3695 K	T_v=5828 K
1	1µs	2 µs
2	0,2µs	0,6 µs
3	90 ns	0,2 µs
4	60 ns	100 ns
5	40 ns	60 ns
6	30 ns	50 ns
10	18 ns	30 ns

Table 4. Appearance time (in ms) of the liquid phase and the vapor phase as a function of qv for tungsten

q_v $(10^{11}$W/m$^2)$	T_m=3695 K	T_v=5828 K
1	80	200
2	40	70
3	27	50
4	20	43
5	16	36
6	15	25
10	09	15

Table 5. Appearance time of the liquid phase and the vapor phase as a function of qs for copper

$q_s(10^{11}$W/m$^2)$	T_m=1356 K	T_v=2868 K
1	0,5 µs	1 µs
2	0,1 µs	0,5 µs
3	50 ns	0,1 µs
4	40 ns	90 ns
5	20 ns	50 ns
6	15 ns	40 ns
10	10 ns	20 ns

Table 6. Appearance time (in *ms*) of the liquid phase and the vapor phase as a function of qv for copper

q_v 10^{11}W/m^2	T_m=1356 K	T_v=2868 K
1	40	90
2	19	50
3	14	30
4	10	22
5	08	18
6	06	14
10	04	10

Table 7. Appearance time of the liquid phase and the vapor phase as a function of q_s for aluminum

q_s $(10^{11}$W/m$^2)$	T_m=933.3 K	T_v=2782 K
1	0,1µs	0,5 µs
2	40 ns	0,1 µs
3	20 ns	50 ns
4	10 ns	40 ns
5	8 ns	30 ns
6	5 ns	25 ns
10	4 ns	13 ns

Table 8. Appearance time of the liquid phase and the vapor phase (in ms) as a function of qv for aluminum

q_v $(10^{11}$W/m$^2)$	T_m=933.3 K	T_v=2782 K
1	20	65
2	10	35
3	06	22
4	05	17
5	04	13
6	03	11
10	02	07

The main findings in our paper is that Joule heating alone is not able to explain the rapid heating to the melting point and vaporization point during some nanosecond and consequently the cathode spot is heated mainly on its surface by the positive ions.

In literature we can find many numerical models of the vacuum arc cathode spot [1, 4, 5, 13, 14, 17-25]. The most recent and complete nonstationary numerical models of a vacuum arc cathode spot are those developed by Wang and co-workers [19-21,]. In [19] Zhang et al used some parameters obtained in our works for with a stationary model of the interaction of a low current vacuum arc with a copper cathode [see 5, 17, 18]. They confirm our conclusion already obtained in [2, 5, 18] on the importance of surface heating with positive ions in comparison with joule heating and that the surface heat power density must be larger than $1×10^{12}$ W/m^2. In [20, 21] they studied the development of a cathode spot in vacuum for a copper with arc current of 1 to 6 A. They found a surface heat power density value between 1.5 and $3×10^{12}$ W/m^2 and a maximum temperature up to 5342K with a cathode crater from 1.4 to 4.1μm.

Kaufmann [22] developed a detailed numerical simulation of a copper cathode spots in vacuum arcs. Their model describes the initiation and development of a cathode spot in a high-current vacuum arc taking into account the motion of the molten metal under the effect of pressure exerted by the plasma and the Lorentz force. Their results showed three phases of the spot life cycle. The ignition phase is characterized by a rapid increase in the cathode temperature up to 4700–4800 K and lasts for approximately 5 ns on a cathode with a microprotrusion and 8 ns on a planar cathode. The surface heat power density was $1.1×10^{12}$ W/m^2 corresponding to a positive current density of $1×10^{10}$ A/m^2. The expansion phase is characterized by a stabilization of cathode surface temperature and an increase in the spot current. During this phase the molten metal formed is displaced from the center of the cathode spot by the pressure exerted by the plasma. This is the crater formation phase lasting about 25 ns. After this time the crater expansion stops because of the heat removal into the bulk of the cathode due to thermal conduction and finally the jet development phase in which a liquid-metal jet is formed under the effect of fluid inertia. The total spot lifetime is about 60 ns.

In references [23-25] with a non-stationary model we can find that development of a cathode spot in vacuum arc of some micrometers during some nanoseconds, the power heat surface density must be more than $1×10^{12}$W/m^2.

Conclusion

In this work we simulated the heating of an electrical contact by a vacuum arc. The study was carried out for different metals (copper, aluminum and tungsten) and different arc lifetimes. The main results obtained are:

-The contact is heated and vaporized principally by the surface heat source of the positive ions coming from the arc plasma. The volumetric heat need at least some *ms* to heat up the contact to the vaporization temperature.

- For a value of $q_s = 1{\times}10^{12}$W/m^2, the appearance times of the liquid phase and the vapor phase are 18 ns and 30 ns for tungsten, 10 ns and 20 ns for copper and 4 ns and 13 ns for aluminum, respectively.

-In vacuum arc the surface heat power density is at least some 10^{12} W/m^2.

-The order of magnitude of these spot lifetimes and heat power densities are consistent with those obtained experimentally by Mesyats [4] and Jüttner [10-12] and also those found with numerical models of many authors [17-25].

Authors: *PhD student, Redouane. Mehimda, University of Sciences and Technology of Oran, ''USTO-MB'', BP 15 El M'Naouer, 31000, Oran, Algeria, Email:redouane.mehimda@univ-usto.dz;*

Dr.Mohammed. Messaad, University of Sciences and Technology of Oran,'' USTO-MB'', BP 1505 El M'Naouer, 31000, Oran, Algeria, E-mail:bmessaad@yahoo.fr;

Dr.Mokhtaria. Si ali, University of Sciences and Technology of Oran,'' USTO-MB'', BP 1505 El M'Naouer, 31000,Oran, Algeria , E-mail: mokhtaria.siali@univ-usto.dz.

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